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KAPSARC – Tensile Fabric Building Skin

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Abstract

Zaha Hadid Architects and Arup have designed an iconic building in Riyadh Saudi Arabia known as the King Abdullah Petroleum Research Centre. Various departmental edifices are formed into a contiguous closed architecture by spanning the 'streets' and 'courtyards' between the buildings with translucent, double-skin membrane cells.

The concept is to provide shade and ventilation without obscuring light or allowing direct penetration of sunshine. The resulting structural skin is an intelligently arranged composite of steel and fabric, random and organic in appearance and with a daring sculptural form.

The challenge to the engineering team was to harness a repeatable structural strategy across a large range of varied geometries. The challenge to the form-finding and patterning team lay in creating a large family of coherent shapes of conical membranes where within each cell there is very varied pre-stress and graded compensation required. The challenge to the membrane provider was to identify a glass-PTFE fabric that would provide the translucency and strength required by the architect's demanding specification. The challenge in fabrication and installation was to produce the extreme shapes and set them perfectly on site.

This paper will illustrate how these challenges were successfully met.

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1. The Concept

Zaha Hadid Architects and Arup have designed an iconic building in Riyadh Saudi Arabia known as the King Abdullah Petroleum Research Centre or KAPSARC. A grouping of departmental buildings is formed into a contiguous, closed architecture by spanning the streets and courtyards between the buildings with translucent, double-skin membrane cells.

Fig. 1. The main buildings of the KAPSARC complex

In addition to the 50 cells comprising the courtyard canopies of the main buildings, other elements of the fabric engineering contract were a series of related canopies over the entrance gate-houses and large ranks of shading canopies over the car parking zones.

Fig. 2. (a) Entrance canopies; (b) Car Park canopies

The rigid, ornamental skin of the research centre's buildings is contrasted with membrane covered translucent cells that cover the spaces in between. The concept is to provide shade and ventilation without obscuring light or allowing direct penetration of sunshine. The resulting structural skin is an intelligently arranged composite of steel and fabric, random and organic in appearance and with a daring sculptural form.

Fig. 3 Courtyard canopies, interior.

The hexagonally shaped cells of very varying dimensions are arranged in a continuous, organic, crystalline looking layout that spans the major central courtyard area and the streets that are formed between the major blocks of the building complex. The spaces and thoroughfares below the lofty canopies are landscaped and undulating. A pattern of light and shade moves daily across the different levels and surfaces of this architecturally beguiling space. The hot, glaring exterior transitions to a cool, filtered interior.

Fig. 4. Aerial view of KAPSARC complex.

2. The Design Team

The client and principal design team were Saudi ARAMCO who commissioned the offices of Zaha Hadid Architects and Arup to provide the 'Issued for Construction' design and act as consultants in its development. The executing consortium for the fabric, fittings and secondary steelwork package of the canopies comprised a Riyadh based membrane contractor; membrane analysis, detail design and engineering by one German and two British engineering offices and steelwork fabricated in the UAE. The over-arching architecture and geometries were fairly fixed, but refinements to negotiate conflicts and achieve the practical execution were reached via a very positive collaborative feedback loop with both consultants. This two-way street allowed the architectural principles and engineering to inform the detailed design, which in turn informed the consultants of what was practically possible. This led to a number of mutually agreed compromises, particularly in areas of stress relief through small changes in the perimeter geometry and in the best fit of material strength and translucency from the available fabrics on the market.

3. The Principles

For all three membrane zones the principles of the architectural design can be described as one: a deep perimeter beam provides upper and lower boundaries to fix double-skin semi-translucent membranes. The double skin serves a number of goals: it forms an insulation layer against the harsh sunlight, it obscures the sharp relief of seamlines, hides the supporting steelwork and yet creates a roof cover that feels lightweight and is light transmitting. The resulting gap between the membranes is of the order of 0.5m to 1.0m and contains an unseen steel structure. For the car parks, columns carry the cantilevering parasols, whose undulating shapes create modest double curvature and hence stability in the membranes. The Entrance canopies are a more traditional cone shape with a large central opening.

Fig. 5. (a) Car Park canopies and (b) Entrance canopies showing deep perimeter beam.

The main courtyard canopies take the cone principle into a new dimension by severely tilting the prominent central opening so that half of the cone is ascending to a South-orientated highpoint, while the other half is pulled downwards, inverting the shape. The orientation of the aperture is towards the North and allows cooler air to penetrate.

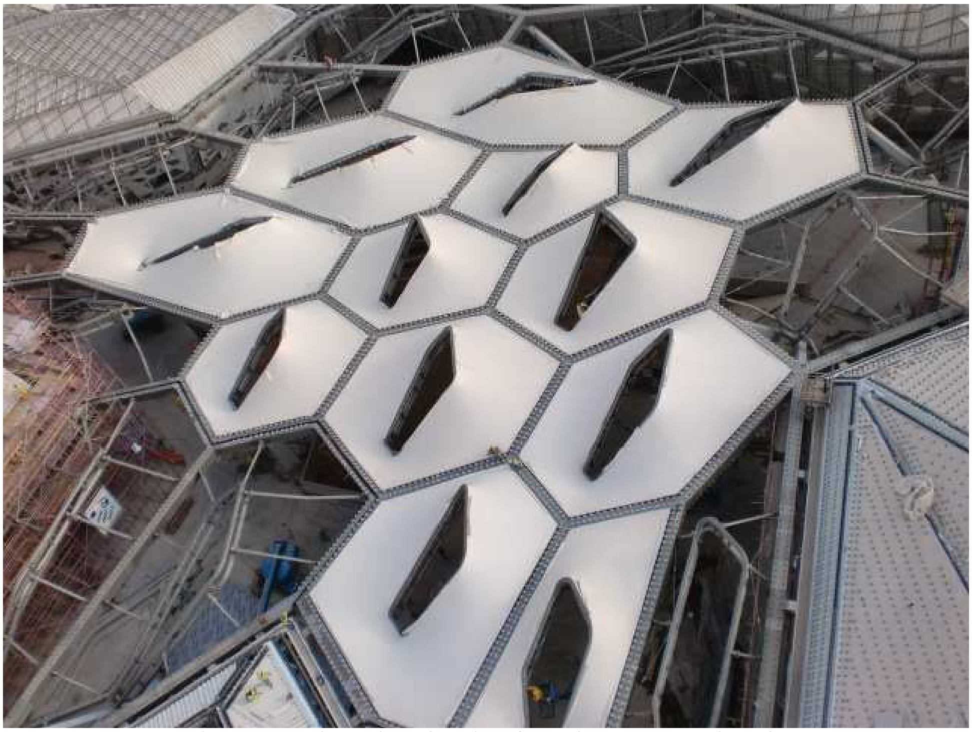


Fig. 6 Courtyard canopies; orientation of central apertures towards north.

4. Structural Strategy

The challenge to the engineering team was to harness a repeatable structural strategy across a large range of varied geometries. Within each of the three genres of canopy we opted to undertake some preliminary analysis of the largest, the smallest and the most extremely shaped cells in order to understand the envelope of parameters we would be designing for. It was economically paramount that the design strategy would apply everywhere so that there would be no expensive surprises as we worked our way through the design of individual cells.

The membrane skins of the car parks, with their less extreme shape, contained linear bracing struts. The relatively flat areas of the membranes were found to deflect enough to create clashing, which was solved with a bump-rail to cushion and absorb deflections that would otherwise have made contact with more aggressively-shaped parts of the structure. All membrane fixings were required to be hidden within the structural envelope. A discreet gutter system channels rainwater down integrated downpipes in the columns. Cladding and lighting units give a crisp appearance to the finished design. To achieve the fabric and fittings detailing in an economical way it was possible for our collaborating engineer, Art Engineering in Stuttgart, to develop a CAD algorithm that could work its way along the linear system lines, thus producing 3D models of the fabric tensioning rails and clamped edges for the steel fabricator.

The algorithm was developed as a Visual Basic script which would examine the primary steelwork model and apply parameters. The outcome was to introduce the rails with support stanchions at a desired interval. Collision checking would modify the parameter to placing the support to either side of an obstruction.

Fig. 7. Car Park canopies

On the Entrance and Courtyard canopies the composite structure of hidden steelwork and membrane skins was much more complex and geometrically convoluted. The principles for both were very similar and I will focus on only the more severely shaped courtyard canopies to illustrate this.

The common theme to the canopies was the horizontal, hexagonal perimeter to each cell formed out of a fabricated box of nearly one metre depth. The inclined ring forming the ventilation aperture was a twisted pentagon that required structurally supporting by struts. The upper and lower membranes would attach to the respective upper and lower perimeters of these two boundaries leaving a gap of less than a metre between.

The size of the irregular hexagon cells varied between 13m across on a fairly regular hexagon shape to some very narrow cells of up to 42m in length. Analysis of a sample of larger and smaller cells gave early indications of a range of membrane stress regimes. Influencing factors were not just the sizes of the cells, but the geometries of pentagon inclination and how tightly these were radiused . Thus the loadings to the supporting steelwork also had a spread of values. Eventually it became possible to rationalise the strut tube sizes and flanged connection details to just two engineered solutions.

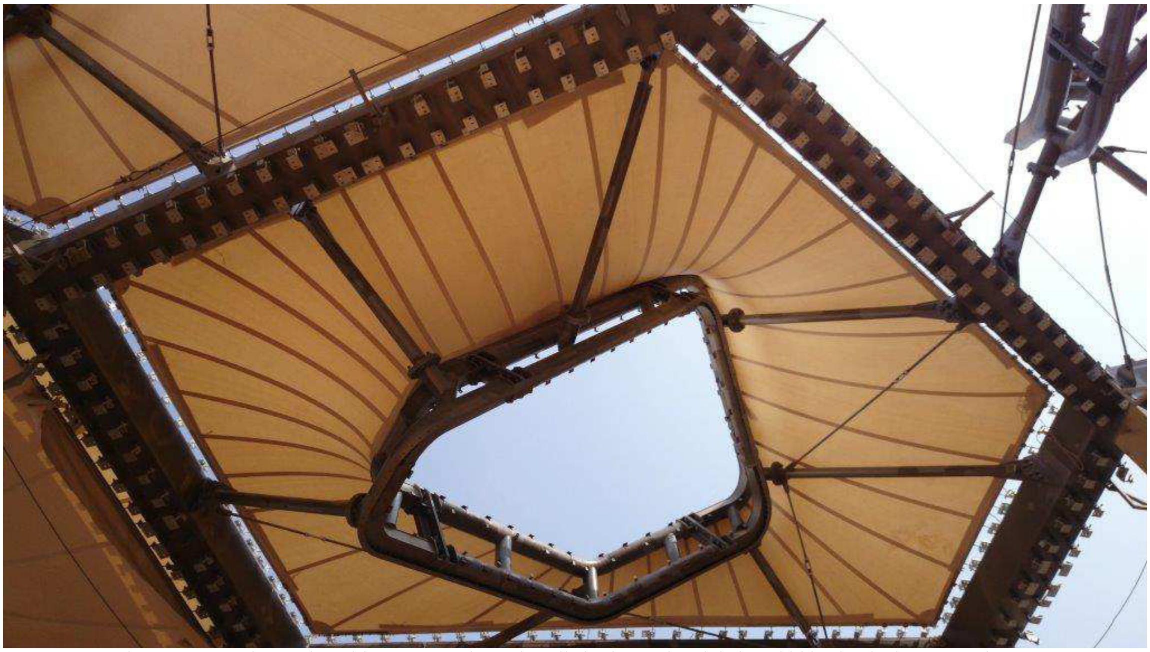


Fig. 8. Courtyard canopies with upper membrane installed. The steelwork is later hidden by the lower membrane.

It was confirmed from the exploratory form-finding, that the fabric attachment to the edges of the steel box section would demand an offset to avoid clashes. An adjustable perimeter detail would need to be developed that would allow the membrane to leave the boundary at the required inclination without any conflict with the steelwork. The solution was to use a continuous keder profile, which is tensioned outwards to the perimeter on articulating studs. The continuous aluminium extrusion profile twists with the membrane and membrane deflections are absorbed via the rotating connection. The corners required a reinforced connection or membrane plate that would still connect seamlessly to the universal perimeter hardware.

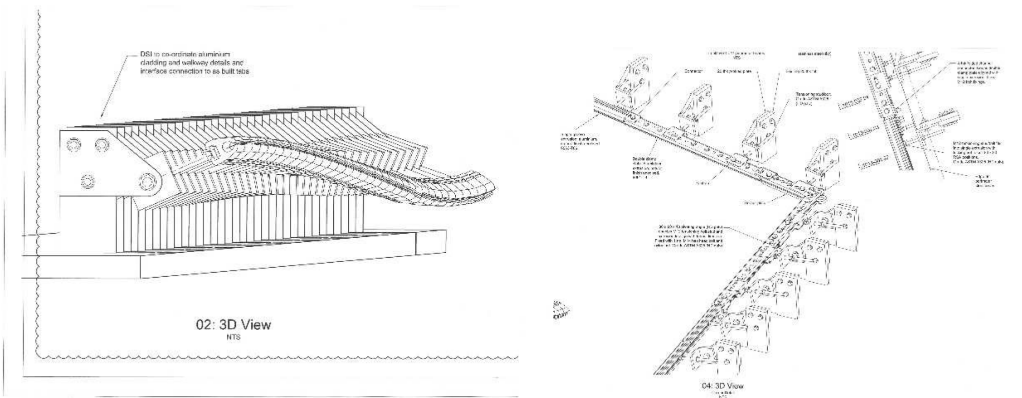


Fig. 9 Perimeter connection: (a) twisted keder profile and articulating studs; (b) perimeter offset hardware.

At the inner perimeters of the pentagon ring the fabric could be clamped to the upper and lower edges, but needed to interface with a gutter channel and cladding detail. The pentagon rings have radiused corners that were generally too sharp to be formed out of rolled hollow section. This then demanded a fabricated boxed plate and splice design contained within a limited volume, while respecting the continuity of the fabric clamping edges. There was also the issue of the strut connection to the steel hexagon perimeter, which required design coordination to works by others which was already being erected on site.

Fig. 10. Typical steelwork details: plate construction on tightly radiused corners and gusset connections to perimeter steelwork.

The form-finding of two offset membranes showed that space between the skins would vary, sometimes becoming very narrow and would occasionally require non-linear strut members in order to pass through the gap and maintain clearance on membrane deflection. Cranked struts would be adopted where curvature was very tight. Soon it would become time to rationalise the design so that the next phase could be tackled in an economical manner.

5. Fabric: analysis, selection and design

Running concurrently, there was a comprehensive form-finding and stress analysis programme ongoing with Tensys. Architectural approval from Zaha Hadid Architects was very sensitive and mainly concerned with consistency of form and curvature. We were trying to match forms that had been developed using entirely different software that would not be taking the stresses in the membrane into account. Early analyses showed that stress concentrations could be very high in certain zones of the membrane. Typical warp prestress values would vary between 3.0 kN/m and 13.0 kN/m. Maximum loadings were generally under wind suction loadcases where peak warp stresses approaching 30.0 kN/m were observed in the analysis model. The maximum permissible stress in the fabric was 35.0 kN/m.

To achieve certain curvature, a high warp to fill pre-stress ratio would be required, which would generally manifest itself at the peaks of the pentagon ring. The introduction of surface cables was considered to bring the surface tensions to acceptable levels. However the ridging effect and the technical difficulty of arranging pockets for the cables was not a desirable outcome. There would also be the inconsistency of the visual presence of the cables on the lower membranes, which the architect was keen to avoid. Another possibility was reinforcement by having multiple plies of fabric. The solution lay in compromise; which meant altering the tightly radiused geometries of certain pentagon rings and adopting a fabric product with a minimum breaking strength of 140kN (safety factor 4.0). This was a matter for collaboration and was approved. Thus with some changes to the pentagon ring geometry, the design could proceed with no additional support required on any of the membranes.

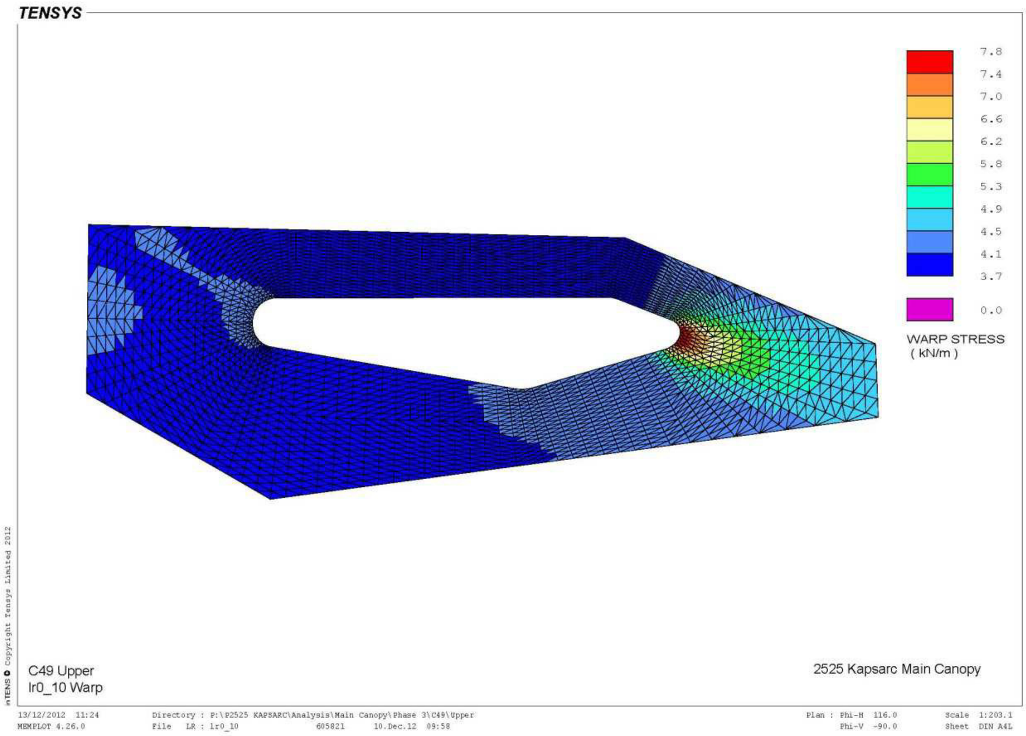


Fig. 11.Typical warp prestress plot on courtyard canopy cell C49 with maximums of 7.8 kN/m. This was one of the largest at 42m in length. Under a wind suction loadcase the stresses in the fabric would rise by a factor of four to around 28.0 kN/m.

Later in the process, the patterning of the membranes would require varied compensations within a single cell and blending these regions to produce a first class result. Biaxial test results for different fabric batches meant very individual compensation values and involved careful tracking of the material through the factory. Most membranes had four different zones of compensation. The biaxial test results showed that the circumferentially orientated fill direction would require a high compensation. Local decompensations around the perimeters were therefore needed, which were index marked to the steelwork and therefore the membranes became easier to install on site.

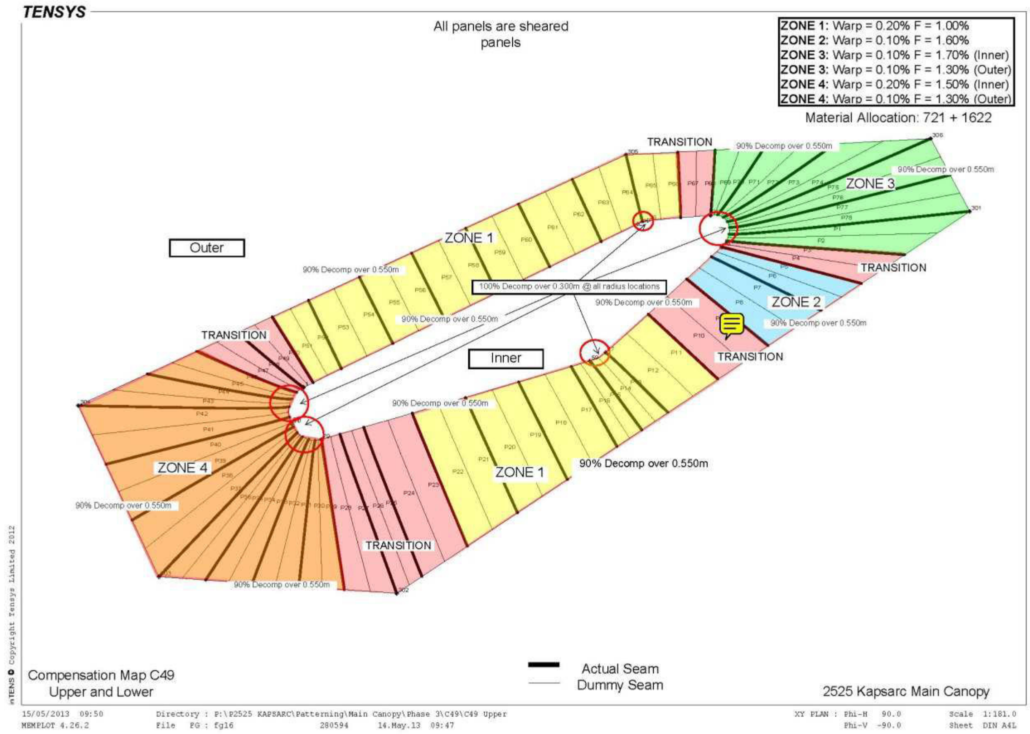
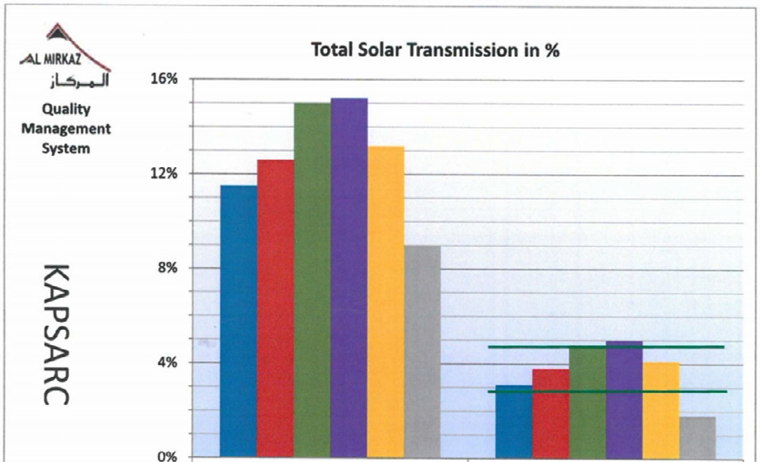


Fig. 12. Compensation map for courtyard canopy cell C49. The radial warp direction required compensations of 0.1% to 0.2%. The circumferentially orientated fill direction required much higher compensations of between 1.0% and 1.7%.

Another concurrent development path was the challenge to the membrane provider to identify a glass-PTFE fabric that would provide the translucency and strength required by the architect's demanding specification and the technical outcomes of the form-finding process. The specification requirements of the membrane fabric for KAPSARC are high. It required a breaking strength of 125kN/m in both warp and fill. A solar transmission for one layer of 16% had been called for. Technical data sheets submitted by the cloth manufacturers, some of which were project specific designs that had not yet been produced or tested, turned out to be misleading. Therefore the fabric contractor had 6 products independently and anonymously tested. None of the fabrics met all of the specification requirements. All the fabrics exhibited a translucency below the specified percentage. Other stringently 'realistic' tests were applied where the fabric is subjected to the bending and creasing to be expected through handling during fabrication, transportation and installation and tested for residual strength. One such test regime is the 'double crease fold' test, which can reduce a fabric's breaking strength by up to 60%. This affects the factors of safety that would need to be employed in the design.

It has already been seen that to avoid patched reinforcement of the fabric or the introduction of surface cables, the fabric employed would need to achieve a breaking strength higher than that demanded by the specification. The breaking strength of a material is a function of the quantity of yarn fibres present and creates a direct relationship to the solar transmission. One way to increase solar transmission, or translucency, is by twisting the yarn's fibres in a closer and more compact way. This effectively creates a thinner yarn, which when woven creates a larger aperture size. Although using the same quantity of glass fibres, effectively the solid part of the material is reduced and the interstices become larger letting more light pass. However there is a strength cost as the tightly packed fibres are more prone to damage during the fabrication and installation manipulation of the fabric, which can be gauged by the residual strength after the crease fold tests.

Once again compromise was the way to a workable solution. It was demonstrated to the design team with several 'lightbox' samples that the final translucency of the combined double-skin membrane drops to quite a low value and that over-optimistic single-ply values only increase the final result by a small margin. When the combined percentage translucency of one layer becomes a factor of the percentage of the second layer and solar reflectance has been taken into account, the fabrics emerge as very comparable. Other factors such as the permissible reduction of safety factors with stronger fabrics and their better visual performance through not requiring any reinforcement ultimately become more important.



	Single Layer Solar Transmission in %	Double Layer Total light transmission
Fabric A	11.5%	3.1%
Fabric B	12.6%	3.8%
Fabric C	15.0%	4.8%
Fabric D	15.2%	5.0%
Fabric E	13.2%	4.1%
Fabric F	9.0%	1.8%

Table 1.2

Comparison of solar transmission through one membrane layer and through two membrane layers. The values for the total solar transmission have been calculated iteratively to take into account reflection, transmission and absorption.

Fabrics C, D and E approach the specified solar transmission values and their combined double layer transmission values lie within less than 1% of each other.

Fig. 13. Bar chart of single and double layer solar transmission. Submitted as part of a detailed laboratory testing summary report which evaluated 6 fabrics anonymously. Although it did not exhibit the highest translucency, Fabric 'E' was chosen when breaking strength and post-abuse residual strength values were taken into account.

The fabricator was thus able to convince the architecture team that a locally sourced fabric Obefolon 1200K from Obeikan would provide the best overall outcome.

6. From Design to Fabrication

So now our composite skin had a viable membrane outer form and strength, we had a repeatable structural strategy and the form-finding of the 50 membrane shapes had been approved. It now became possible to start a quasi production-line of engineering, detailing and steel fabrication that could progress through the sequence of phased cell clusters as demanded by the main contractor's build programme. Similarly fabric production, biaxial testing and batch logging could be mapped to the form finding and compensated patterning of the 100 membranes.

One medium-sized cell was adopted as the test-bed. Certain learning curves were played out in the engineering and detailing of this first cell, and likewise in the fabric patterning and fabrication processes. It duly became the first cell to be erected on site and receive its membrane skins. The first cell was slow to achieve, but soon the flow of information became accelerated and in not many months all the designs had been completed and the steelwork and membranes were in various stages of fabrication and installation.

Fig. 14. Courtyard canopies; installation of first cell.

The steelwork installation took place on a very busy building site. One complication was that the interfacing gusset plates had to set out and welded in situ before the completed pentagon rings and strut assemblies could be craned into place. The membrane installation took place from underslung nets and required the rolled up ring-shaped packages to be manoeuvred into place before the pentagon perimeters could be clamped and the outer boundaries tensioned to the hexagon rings.

Fig. 15. Building site during installation.

7. Conclusion

The final result meets the architect's aesthetic vision. A complex engineered structural skin has been achieved while preserving the essence of a translucent covering. Whether viewed from above or below, the daringly shaped membranes appear to magically suspend the central openings; effectively disguising the internal supporting structure.

Fig. 16. Almost completed courtyard canopies. Due to the absence of the cover flap on the upper membrane, daylight silhouettes the perimeter clamping detail.

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International Contracting Company (KSA): Steelwork project management and erection
Mabani Steel (UAE): Steelwork Fabrication
Obeikan (KSA): Fabric manufacture
Labor Blum (GER): Fabric testing

Fig. 17. Design intent; computer rendered image by Zaha Hadid Architects